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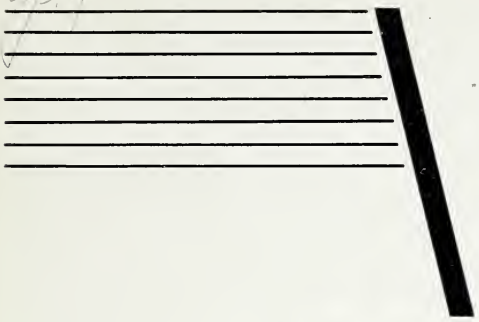

Stratified Flow in Reservoirs and its Use in Prevention of Silting

Miscellaneous Publication No. 491
United States Department of Agriculture

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Foreword

Food crops, meat, wool, poultry, eggs, fibers, oils, are implements of war, like planes, munitions, and ships. The war program calls for increased production of these essentials. The goals must be reached, and it is necessary to get production with what land is available through good farming and livestock management with the assistance of soil and water conservation activities. No other way has been found. In order to do this, it is going to be necessary to overlook nothing that promises increased production.

In the program for meeting the needs of the war, reservoirs—receptacles for the conservation and utilization of rainfall—will have a place. Hundreds of reservoirs will have to be constructed for use in irrigation, for power production, for domestic water supply, and for watering livestock. The increased demands will call for reservoirs of all sizes, some very large. Some are under construction now; others will be building tomorrow, next year, and the year after.

The menace of sediment depleting the capacity of reservoirs of all sizes is not generally well understood. There is need for a better understanding of the whole sedimentation problem—every phase of it—by the public and by technicians, some without much previous practical experience, who will be constructing dams. This is especially true with respect to new information, as that recently acquired through surveys and research in the sedimentation field.

The practical possibilities of conserving capacity by using underflows to pass large quantities of silt through reservoirs lie largely outside the field of experience. Many dams that impound large volumes of water have been built with no provisions whatever for discharging water and silt at low levels, and where such provisions exist they are not used for this purpose. If past practices are followed, the new reservoirs will have the same failing, thus needlessly shortening their useful lives by from 10 to 30 percent. Therefore, every possible effort to protect them from filling with sediment must be made.

This publication presents new conceptions and new methods for protecting the larger of the reservoirs that may be built this year and next as part of the war program. It puts in the hands of engineers, agronomists, and others an increased knowledge of a subject of importance in the field of good land use and good water use.

HUGH H. BENNETT,
Chief, Soil Conservation Service.

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Stratified Flow in Reservoirs and its Use in Prevention of Silting

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INTRODUCTION

The stratification or layering of water impounded in lakes and reservoirs is widely recognized as a common natural phenomenon. In its most familiar form it is produced by differences in temperature that cause corresponding differences in density. A warm surface layer, at one time or another, has lured almost every swimmer into an extremely cold pool, and thus has introduced him to stratification. Such a deceptive layer is possible because, at all temperatures above 39.2° F., the warmer the water is, the less it weighs. In other words, as it grows warmer it expands and, therefore, decreases in density. In sheltered ponds a warm stratum may be only inches thick, but in the open sea or in lakes, where wind and waves can work effectively, isothermal layers of considerable thickness are frequently developed.

Stratification that results when dissolved or suspended material produces the essential difference in density is less familiar, but of much greater economic importance. Few farmers care whether the water they use in irrigating their field is warm or cold, but they may be greatly concerned if it is

[1] The cooperation of the staff of the U. S. Bureau of Reclamation at Boulder City, Nev., has been invaluable in the preparation of this paper. Manly Natland of Long Beach, Calif.; Mrs. Milton C. Jorgenson of Watertown, S. Dak.; F. W. Brandt of Spearman, Tex., and C. E. Recknagel, Western Springs, Ill., have been most generous in supplying illustrative material.

salty or very muddy.[2] And yet the water delivered may very well be either good or bad, because a particular reservoir may contain, simultaneously, layers that are warm, cold, fresh, more or less saline, clear, or extremely muddy.

Such complex stratification is, in fact, the usual condition at Lake Mead, where the delightful temperature of the surface layer attracts bathers in summer and the coolness of the temperature of the strata at the depths from which water is withdrawn makes it possible for trout to thrive below Boulder Dam. The transformers, the generator bearings, and in summer the powerhouse offices, are cooled by circulating lake water. Some of the coldest water, however, is slightly brackish and forms a distinct stratum beneath which is a submerged and very muddy lake.

Such a submerged muddy lake is possible because water strata, unlike rock strata, are mobile. The densest water naturally sinks to the bottom where, if there exists a slope, it may continue to flow until its progress is checked, perhaps by a dam or some other obstacle. A moving stratum of this kind is called a "density current," because its slightly greater density gives it the power of motion.

Many submerged lakes of turbid water trace their origins to very muddy rivers. It has been known for a long time that, because their velocities are greatly reduced and they are no longer able to hold the coarser particles in suspension, sediment-laden streams tend to build deltas when they enter a body of still water. Other things being equal, the smaller a particle is the longer it may be kept in suspension and the farther it can be carried into a body of still water. Ordinarily, too, the farther a river penetrates a lake, the greater is the reduction in its velocity, so that, eventually, it is unable to hold even the finest sediment in suspension.

This explains why deltas are composed chiefly of particles that are coarse as compared with those deposited on the adjacent floor of the lake and why deposits tend to grow finer with distance from the inlet, but it fails to explain how submerged muddy lakes are related to sediment-laden streams.

The Colorado River at times carries enormous quantities of fine silt, clay, and colloidal material. When it enters Lake Mead the coarse silt and sand are deposited on the delta. Most of the finer particles may be held in suspension. Under such conditions the river water continues to be very muddy and, therefore, appreciably denser than the clear water in the reservoir. Consequently, it plunges beneath the surface (fig. 1) and continues to flow along the sloping reservoir bottom as a submerged sediment-laden stream, a moving stratum, that is frequently able to keep fine materials in suspension until it comes to rest as a muddy lake in the deepest part of the reservoir.

[2] Relatively few farmers who irrigate live so close to snow-capped mountains that they must use water cold enough to retard their crops. Muddy water, however, sometimes presents serious difficulties, because the fine sediment either settles or filters out of suspension, fills the openings into the soil, and seriously decreases the rate of infiltration.

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FIGURE 1.—A motorboat approaching the point where muddy water from the Colorado River (lower right) disappears below the blue surface of Lake Mead.

The difference between sediments deposited in the delta area and those that are carried far into the lake by submerged flows is pronounced. A sample taken from a deposit in upper Lake Mead contained 5 percent fine sand, 55 percent very fine sand, 39 percent silt, and 1 percent clay, by weight. In contrast to this, 26 samples taken from the submerged muddy lake in the lower end of the same reservoir contained, on an average, 23 percent silt and 77 percent clay and colloidal material.

Large Reservoirs Serve Many Purposes

Ordinarily a large reservoir is not created for a single purpose. In the arid and semiarid West its primary use may be to conserve water for irrigation, but at the same time it frequently must provide power and water for industrial and domestic needs. It may also be a vital part in a system of river regulation or flood control, valuable recreation center, and a refuge for wildlife.

Stratification affects all of these interests, and yet it is often impossible to give them any special consideration, because the outlets of many reservoirs have been constructed as if the impounded water were all of one quality and as if only the quantity discharged should be controlled. Given a versatile outlet system and an inventory of the strata within a reservoir an operator who has familiarized himself with the behavior of density currents, that is to say of layers in motion, can do much toward providing consumers with the quality as well as the quantity of water they desire.

It is becoming increasingly evident that a reservoir is far more than a large water container with an adjustable outlet. It is a machine, a huge machine upon which an exceedingly complex civilization is growing steadily more dependent for food, drink, power, protection from floods, and even for recreation. Its most efficient operation may depend largely upon a knowledge of the behavior of density currents and upon the operator's abilitity to make use of them. By skillful planning he may be able to conserve a part of the storage capacity that normally would be destroyed by the deposition of fine sediments. It is entirely possible that he could supply water of a kind that would seal new canals, destroy weeds in old ones, or even improve the soil of sandy farms.

There are two principal reasons why it usually is impossible to operate existing reservoirs in this manner. In the first place, the outlet works of today were designed almost universally with a complete disregard for the opportunities presented by the phenomenon of stratified flow.[3] In the second place, the surprisingly small amount of special knowledge that the operator must have has not been made available.

At the present time, meteorologists of the comparatively new "air-mass" school and a few specialists in the field of fluid mechanics form about the only groups familiar with the behavior of density currents. Consequently,

[3] Exceptions are found at several reservoirs used almost exclusively for the storage of domestic water.

much of the pertinent literature is written with a highly specialized vocabulary that places it beyond the grasp of many who could use it to advantage. To present some of the most usable facts about density flows in terms that may be understood readily by all is the purpose of this publication.

WHAT DENSITY CURRENTS ARE

At the very outset, then, it seems desirable to state what is meant by the term "density current," and to point out that it is used interchangeably with either "stratified flow" or "density flow." When the door is opened between a cold room and a warm one a draft of cold air immediately begins to flow along the floor of the warm room. That draft is a density current. Other factors being equal, cold air is heavier (has a greater density) than warm air, and consequently it flows into the warm room in response to the greater force exerted upon it by gravity. At the same time warm air flows through the upper portion of the doorway into the cold room, as a puff of smoke or a candle flame clearly will demonstrate.

Similarly, iced coffee is denser than that which is hot, and this explains why cream from the same pitcher floats on the one but flows beneath the other. In either case the cream forms a density current, which may be defined rather broadly as a gravity flow of a fluid through, under, or over a fluid of approximately equal density (fig. 2).

FIGURE 2.—A density current of muddy water approaching the dam in a laboratory reservoir filled with clear water.

A river flowing under air is a gravity flow, but it is not a density current because the density of water is approximately 800 times that of air. One fluid is flowing under another, but the two are not of approximately equal density and, therefore, by definition, surface streams are not density currents. If, however, a cold river enters a warm lake it may continue to flow as a separate stream to the lowest part of the basin. If, for instance, the temperature of the lake is 67° F., and that of the river 60° F., the river water will be approximately 1.0008 times as heavy as the lake water, and

the terms of the definition will be fulfilled. The difference in the densities of the two masses of water is at least 10 times as great as has been found necessary to assure stratified flow in experiments conducted in the cooperative laboratory of the Soil Conservation Service at the California Institute of Technology.

These experiments have been made, for the most part, in a glass-walled flume 5 feet long, 10 inches deep, and 2.25 inches wide. Two larger flumes have been used occasionally; one is 10 feet long and 10 inches square; the other is 15 feet long, 34 inches deep, and 15 inches wide. Underflows having effective densities (weight per unit volume of underflowing liquid divided by weight per unit volume of overlying liquid) from 1.0001 to 1.0080 have been investigated. Bottom slopes of from 0.25 to 8.0 percent have been used, and temperatures, carefully controlled, have ranged from 45° to 95° F. Mean velocities of the currents only rarely have exceeded 4 inches per second. Density differences have been obtained ordinarily by the use of fine sediments in suspension, although sugar, sodium chloride, and sodium thiosulfate have been used occasionally, as have differences in temperature.

SOME DENSITY-CURRENT HISTORY

The tendency of cold rivers to underflow after entering warmer lakes attracted the attention in the 1880's of a group of Swiss scientists who noticed that the cold and turbid waters of the Rhine and Rhone Rivers appeared to plunge beneath the comparatively warm and clear waters of Lake Constance and Lake Geneva, where they continue as distinct submerged streams (fig. 3).

Shortly after the first World War, plans were made for the development of the water power of the Alps. The projects required the use, for storage or other purposes, of many lakes which in summer were popular bathing resorts. Since the permanent inhabitants of the area depended almost entirely upon the trade of summer visitors for their livelihood, it was only natural that they should object to these plans on the ground that the diversion of icy streams into the lakes might make them entirely too cold for bathing purposes. A series of laboratory investigations showed conclusively that the incoming cold water would sink until it reached a level where the density equaled its own, and that the warm surface stratum could be conserved by withdrawing the cold water through low outlets or by placing a sailcloth curtain at the entrance to a specially designed head-race channel in such a manner that it would hold back the surface water, and yet permit withdrawal from deeper and colder levels (fig. 4).

Until comparatively recent years density currents were thought to be rare and mysterious phenomena. Today they are known to be common, although, very frequently, they are invisible or else are found in places where direct observation either is difficult or impossible. This is particularly true of the stratified flows that occur in lakes and reservoirs. If their origin is traced to dissolved salts or to differences in temperature they are

cloaked in invisibility; if they spring from muddy suspensions, they usually plunge beneath the surface and flow on unobserved.

In spite of such difficulties field technicians can learn much about them with electric thermometers, conductance cells, current meters, and water samplers (figs. 5, 6). Investigations of this kind are of great scientific value, but they tell very little about the form and appearance of density currents.

FIGURE 3.—A flood of muddy water has just entered the reservoir from the left. Already a density current is moving down a submerged "delta" of sand. The surface layer is slightly turbid and hangs like a thin cloud above the underflow.

Behind the transparent walls of an experimental-laboratory flume all such currents can be created and made visible. Visiting field men often are surprised to find that these currents are seen as easily as the smoke from a factory chimney and are as real as the cloud raised by a car speeding along a dusty road.

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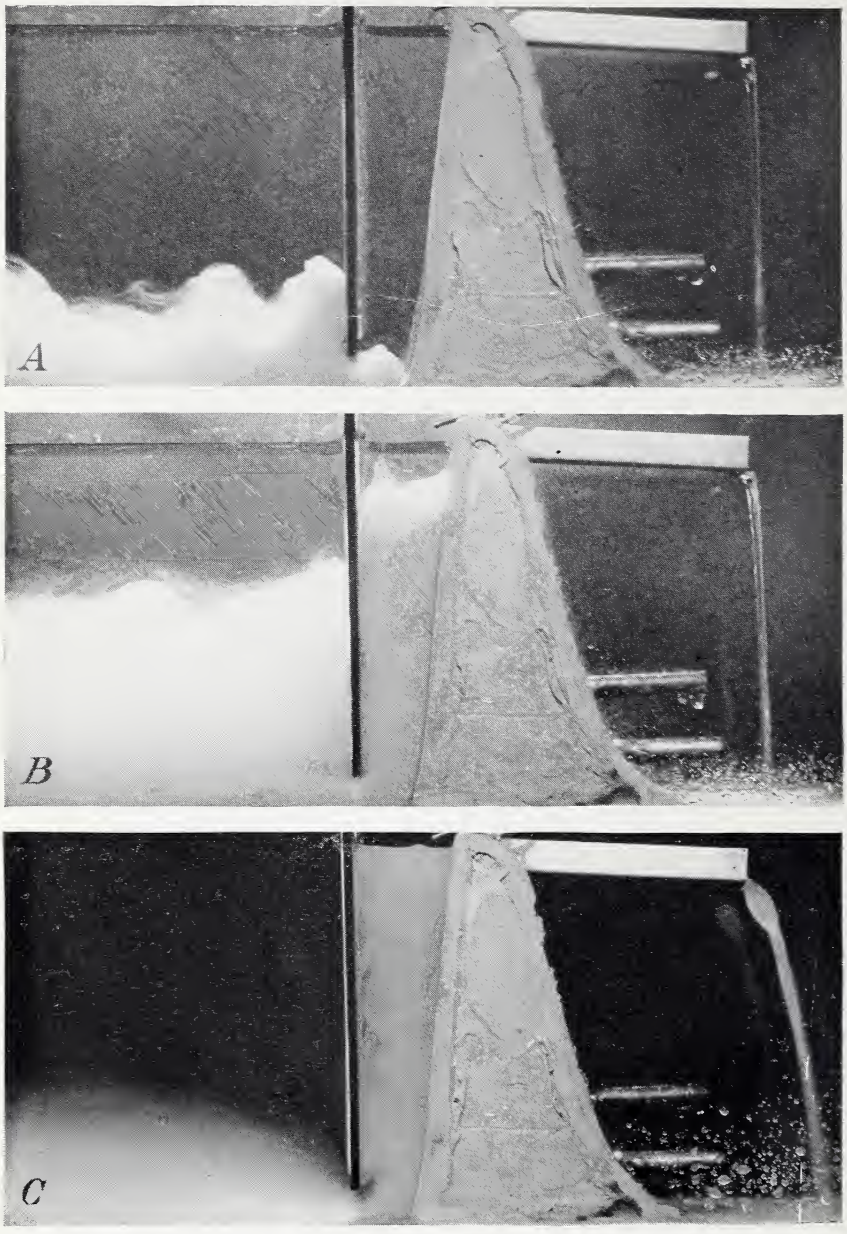

FIGURE 4.—A curtain-type outlet in action: *A*, As turbid density current reaches curtain, clear water is being forced over spillway; *B*, muddy flow climbs toward spillway behind curtain; *C*, muddy water discharging over spillway, while clear water is held back by curtain.

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FIGURE 5.—Turbid water brought almost undisturbed from the depths of Lake Mead in a sampler provided with a transparent wall. Note that sample came from the "interface," the level at which clear and muddy water are in contact.

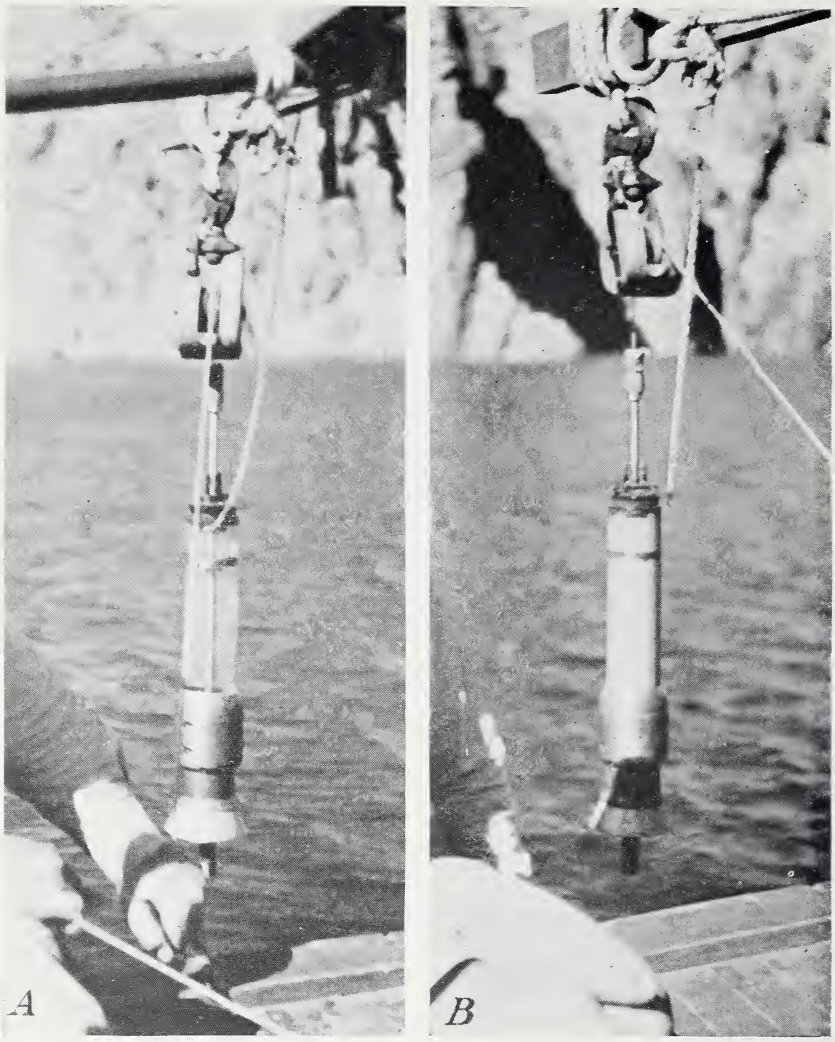

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FIGURE 6.—Samples of water brought from the depths of Boulder Canyon, Lake Mead, June 6, 1941: *A*, from a depth of 449 feet the sampler brings clear water; *B*, from a depth of 455 feet it brings water containing 6.7 pounds of fine sediment per cubic foot.

STRATIFIED FLOWS MANIFEST THEMSELVES IN MANY WAYS

When a visitor from the Dust Bowl watches a muddy density current pass through the flume and remarks that it looks like a miniature duststorm, the laboratory technician sees his experiment from a new angle. A turbid underflow is, so to speak, a duststorm under water, and a duststorm is a turbid underflow on the bottom of a reservoir filled with air. The two are alike in appearance and behavior because each is a density current that owes at least a part of its existence to suspended sediment (figs. 7, 8, 9, 10)

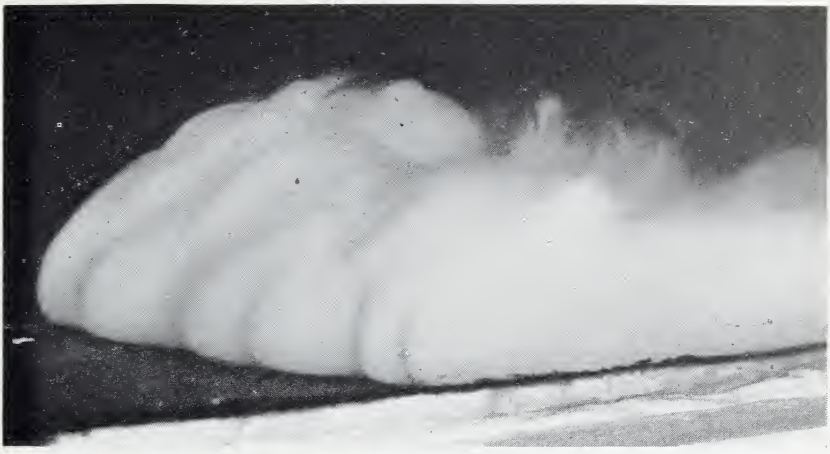

FIGURE 7.—A turbid underflow 2 inches deep advancing along the bottom of a laboratory reservoir.

C. E. Recknagel

FIGURE 8.—A duststorm 2,000 feet deep moving across Nebraska. The bright upper clouds are water vapor.

Mrs. Milton C. Jorgenson

FIGURE 9.—A "black blizzard" in South Dakota.

F. W. Brandt

FIGURE 10.—Spearman, Tex., about to be engulfed by a Panhandle "duster," April 14, 1935.

The meteorologist, watching a current of dyed cold water flow beneath the warmer water of a laboratory lake, remarks that it looks almost exactly like a cold front.[4] It should because it is a type of cold front.

[4] A mass of cold heavy air moving in and displacing a mass of warm lighter air is called a cold front by meteorologists.

The research worker knows that if he had used a stream of salty water the visiting scientist would have made the same remark, because the two currents would have been almost identical in appearance. He knows, too, that they, in turn are transparent duplicates of the turbid underflow that looked like a duststorm.

Frank A. Perret

FIGURE 11.—A "fiery cloud" of gas and volcanic dust moving down the side of Mount Pelee.

Watching these same experiments, the naval officer sees a smoke screen, the whaling captain sees fog banks, the skiing enthusiast recalls the train of powdery snow created and left behind by an avalanche. The engineer describes a cloud of dust that swept across a river when the cliff face was blasted, and the veteran is reminded of the time the enemy used mustard gas. The volcanologist describes the dusty clouds of fiery gas rushing down Mt. Pelee's slopes (fig. 11) and the naturalist understands why water made muddy by a raccoon washing his food drifts lazily to the deepest part of a quiet pool. Watching an underflowing density current is all that is necessary to bring to the mind of each some other underflow.

A Surface Indication of Underflows

The observation of turbid underflows in lakes and reservoirs is usually difficult, even with special equipment, but there is one surface phenomenon that frequently can be observed when an underflow is taking place. At the spot where the muddy river plunges abruptly beneath the clear reservoir, a mass of debris often accumulates to form a floating island or, occasionally, even may become a barrier that reaches from shore to shore (figs. 12 and 13).

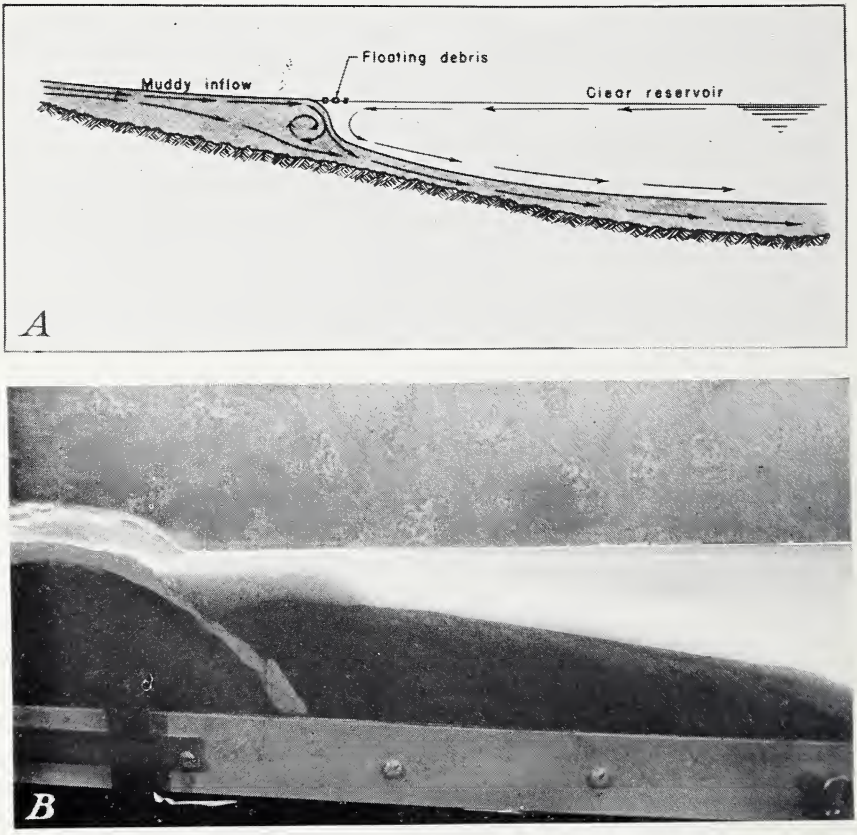

Figure 12.—The beginning of underflow in a reservoir: *A*, Diagrammatic representation of circulation pattern that accompanies underflow; *B*, muddy water plunging beneath surface of reservoir and continuing as an underflow.

The driftwood and other similar material brought down by the river is stopped at this point by the upstream surface current in the reservoir, and the debris brought by the reservoir current is stopped by the inflowing river. It is as if each is refusing obstinately to accept what is offered by the other. In June 1941 a barrier formed in this way completely blocked a canyon section of Lake Mead at a point between 85 and 90 miles above Boulder Dam (fig. 14) and forced upbound boats to turn back.

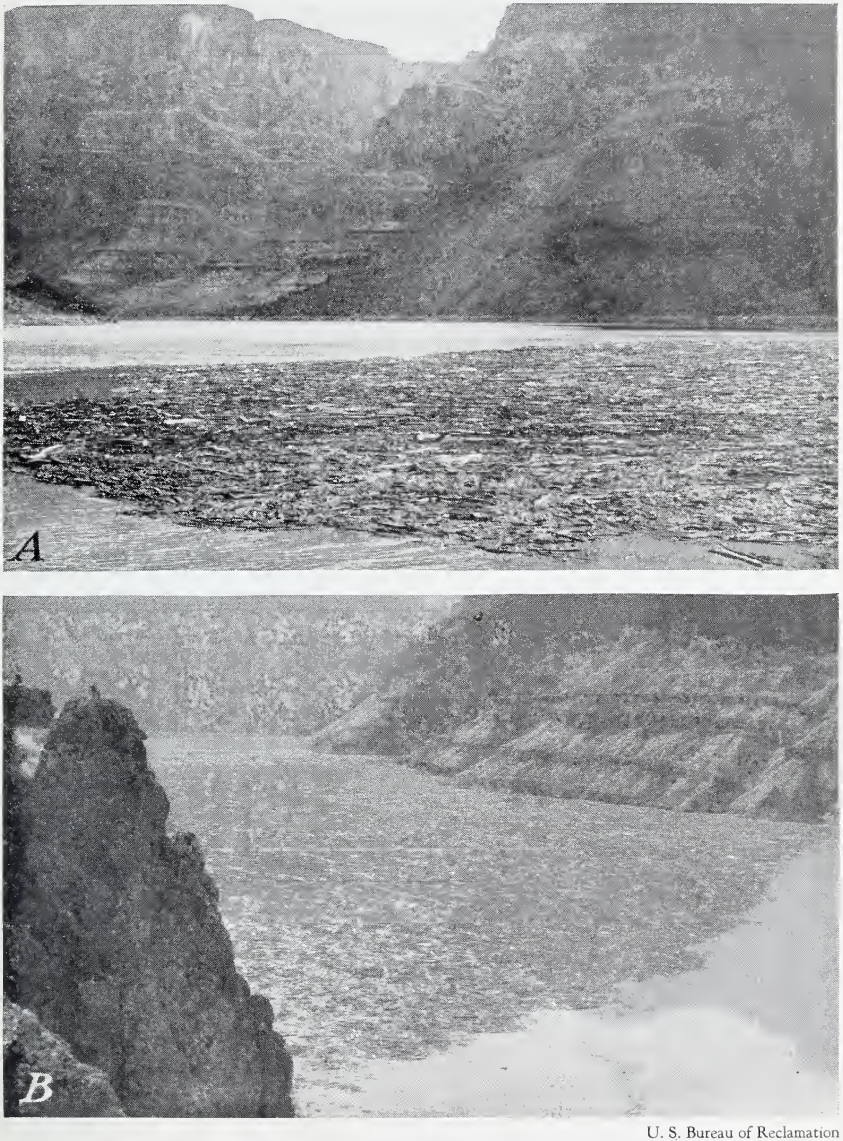

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FIGURE 13.—Driftwood at the beginning of underflow in Lake Mead: *A*, An island of debris, May 3, 1940; *B*, a jam several thousand feet long and reaching from bank to bank, June 5, 1941.

U. S. Bureau of Reclamation

FIGURE 14.—On June 5, 1941, about 87 miles above Boulder Dam, the motorboat Paiute was carried against the downstream edge of a driftwood jam by an upstream surface current. Such a current usually prevails when an underflow is in progress.

OVERFLOWS AND INTERFLOWS

Since density currents of the type just considered are called underflows, it would seem logical to call the remaining two types overflows and interflows. Density-current overflows commonly occur when ordinary streams enter bodies of salt water or when warm streams discharge into comparatively cold lakes. Unless the overflowing water is turbid the phenomenon is invisible. Air travelers who fly along sea coasts frequently catch sight of semicircular areas of muddy water, spreading on the surface of the blue or green ocean like huge tawny fans at the mouth of every flooding stream (figs. 15 and 16). At times the line of demarcation is so sharp that one seems to be looking down on a giant griddle upon which batter has been freshly poured (figs. 17 and 18).

Surface layers of this kind usually are confined to a narrow area along the shore, but notable exceptions are supplied by the Gulf Stream, and by the very similar current of turbid water that extends from the mouth of the Amazon River out over the South Atlantic, where it can be recognized by its color for hundreds of miles. The actual overflows frequently begin far from the seacoast, because the ocean sends tongues of salty water surprising distances inland along the bottoms of the river channels. In the Mississippi and Hudson Rivers these tongues are considerably more than 100 miles long, reaching to New Orleans and Albany.

M. L. Natland and Roger Revelle

FIGURE 15.—Muddy river water spreading out on the surface of the Pacific Ocean off the coast of southern California, between Del Mar and La Jolla, February 22, 1941. Flows from Escondido Creek, San Dieguito River, and Sorrento Creek may be recognized.

M. L. Natland

FIGURE 16.—The Los Angeles River discharging muddy water into the Pacific Ocean at Long Beach, Calif., March 5, 1941.

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FIGURE 17.—A springtime flood from the Santa Clara River flows out on the surface of the ocean near Ventura, Calif., March 14, 1938.

M. L. Natland and Roger Revelle

FIGURE 18.—There is no doubt where muddy water ends and salt water begins as this muddy flow pushes out to sea off the coast of California, near Del Mar, February 22, 1941.

Clouds provide the most familiar example of an interflow. Two or more strata flowing in different directions, differing markedly in temperature and often separated widely by intervals of clear air, commonly are encountered by aviators. Variations in temperature and moisture content are largely responsible for stratification of this kind. In bodies of water very similar phenomena result from differences in salinity or quantity of suspended sediment, as well as from variations in temperature (fig. 19).

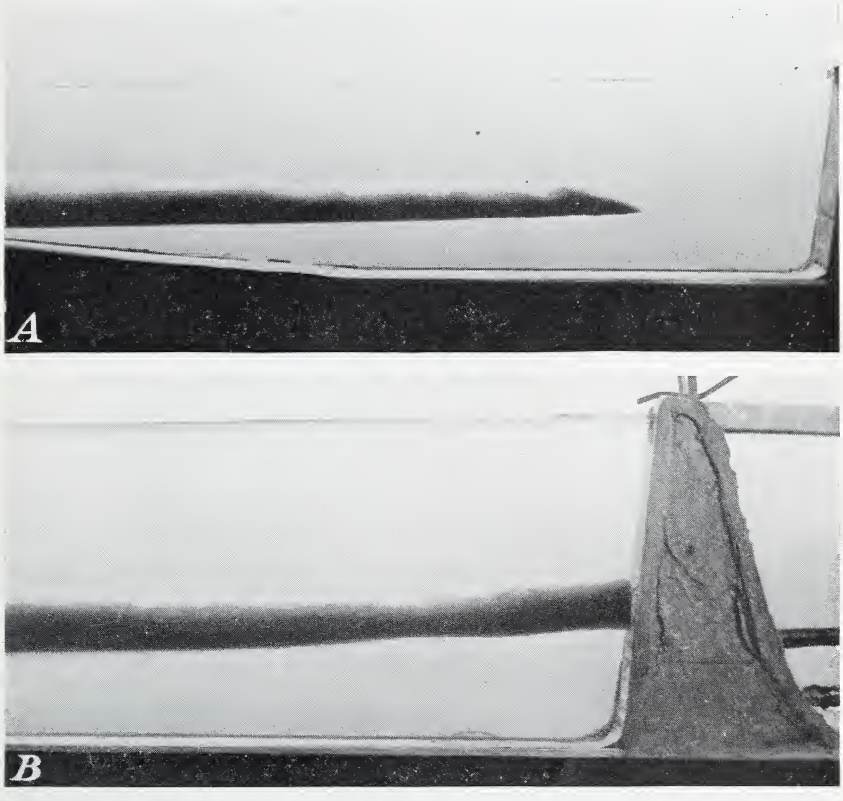

FIGURE 19.—An interflow of silt-laden water: *A*, An interflow is forcing its way along the interface between a layer of fresh and a layer of salty water; *B*, After reaching the dam the muddy layer increases in thickness because the flow of turbid water continues.

When rivers that differ in color unite they may flow side by side as distinct streams for many miles. This phenomenon is possible only when the waters of the two streams have essentially the same density, as might be the case when a slightly turbid river unites with a cooler clearer one. If the difference in densities is as much as a few hundredths of 1 percent, the heavier stream will sideslip rather promptly beneath the lighter one. The surface water, consequently, may continue to be relatively clear for a considerable distance, especially if the rivers are deep and the currents gentle.

Since it is perfectly obvious that a heavy fluid will sink beneath a lighter one, there may be a tendency to dismiss the matter of the behavior of density currents as a problem not worth special attention. Admittedly, the single factor of density difference is sufficient to explain the existence of stratification either in bodies of water or in the atmosphere, but the instant stratified flow begins to take place in liquids it is necessary to explain why liquids sometimes behave as if they were gases. The reasons for this behavior hold the answers to some of the major questions surrounding density currents.

In attacking the problems presented by the behavior of stratified flows it may be well to concentrate attention first on a single kind. Turbid underflows will serve this purpose. They have been recognized in America since 1914, when they were reported as having occurred several times in Zuni Reservoir, N. Mex. Since then, they have been observed in many parts of the Nation, as well as abroad. Certainly there is not one State in the Union in which turbid underflows do not occur.

Although these currents may result from wave action along a muddy shore, they are produced far more commonly by very muddy streams that flow into clear lakes or reservoirs. As it approaches a reservoir, the river behaves in a manner that is thought of as normal. Immediately after entering it expends a large amount of energy in the form of turbulence, as the turbid water mixes with the impounded water.

Thus far everything that happens is what might be expected. Suddenly, however, the diluted turbid river water plunges beneath the reservoir surface, and continues flowing as a separate muddy stream. Everything now appears to be happening in slow motion, and every movement seems exaggerated. If a submerged channel exists on the floor of the reservoir, the muddy current flows in that, climbs to surprising heights on the outside of the slightest bend, even abandons the channel completely at sharp turns,

FIGURE 20.—Turbid underflow falling over a submerged dam.

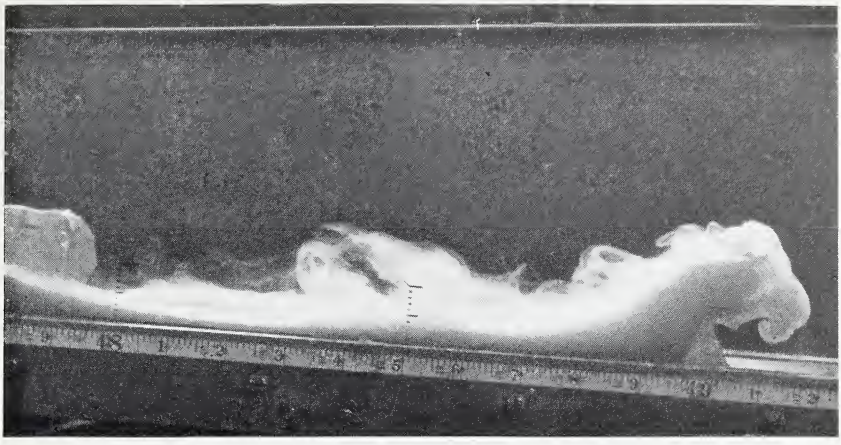

FIGURE 21.—A turbid underflow leaping over a submerged barrier.

tumbles over submerged falls with the deliberateness of a feather settling in calm air, and leaps almost as lightly as a wisp of cloud over seemingly impassable barriers (figs. 20 and 21).

UNDERFLOWS BEHAVE LIKE DUST CLOUDS

The underflow has ceased to act like a muddy river. Everything the current does is far more characteristic of moving clouds of dust than it is of flowing water. In a very real sense it is a cloud of dust—a cloud of dusty water flowing under clear water just as a cloud of dusty air flows under the clear atmosphere.

Its apparent feathery lightness was explained long ago when Archimedes stated that a body immersed in a liquid is buoyed up by a force equal to the weight of the liquid displaced. Archimedes would have been no less truthful if he had used the term "fluid" instead of liquid, because his famous principle applies equally as well to gases as it does to liquids. The turbid underflow is very definitely immersed in a liquid that has a density almost equaling its own and, consequently, it is being buoyed up by a force that very closely approaches its own total weight. Only the suspended sediment prevents it from floating.

For the sake of simplification it has been assumed that temperature and salinity are identical in the river and in the reservoir.

If comparable conditions are assumed for two air masses it is not difficult to see that a dust cloud, too, may owe its greater density entirely to the suspended sediment. Just as the muddy underflow is buoyed up by a force equal to the weight of the liquid displaced, so also the dusty air is buoyed up by a force equal to the weight of the medium it displaces. From the point of view of the physicist the two flows are very similar. Each is composed of a turbid fluid that is being buoyed up by a force so great that the effectiveness of gravity is almost completely nullified and, consequently, they behave alike.

Velocities of different types of underflow are very different. Duststorms commonly travel more than 30 miles per hour, occasionally twice that fast. The field data now available indicate that underflows rarely attain a velocity of even 1 mile per hour, unless they occur where slopes are steeper than those commonly found in large reservoirs. In canyon sections at Lake Mead maximum velocities of about 2 miles per hour have been measured, but

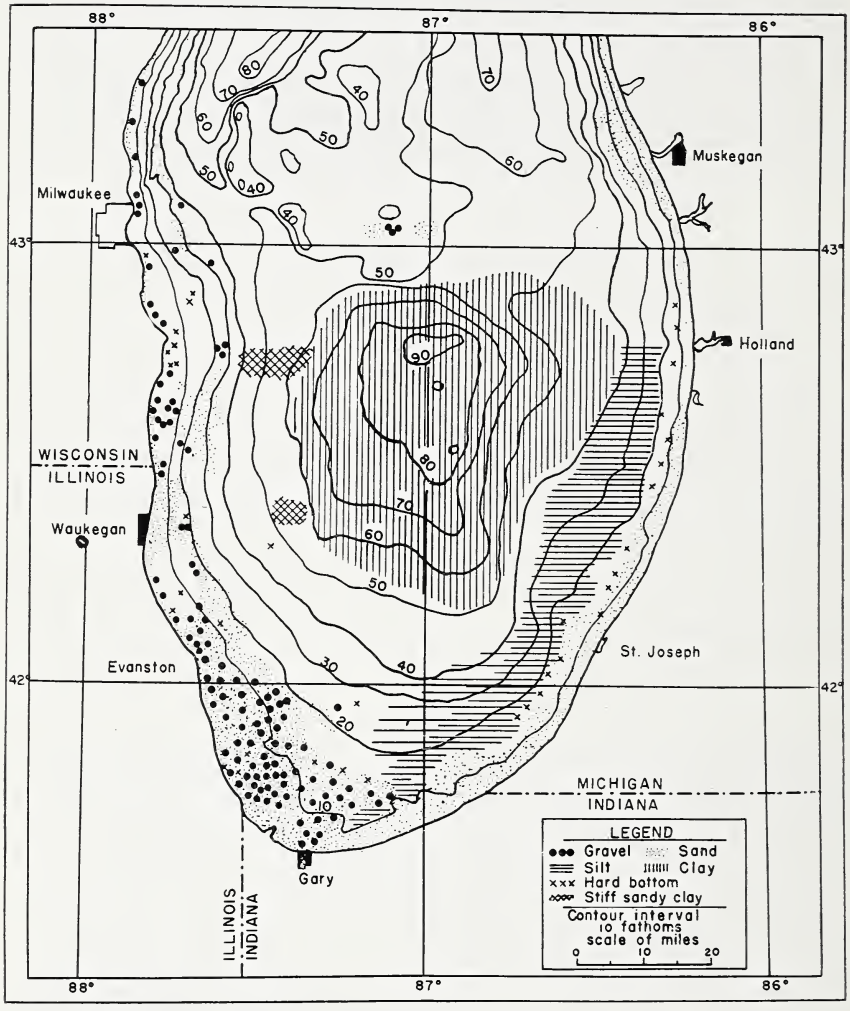

Figure 22.—A reconnaissance map of the southern part of Lake Michigan, showing the areal distribution of sediments. (After J. L. Hough. Contours drawn from the base map, U. S. Lake Survey chart No. 7, 1931.) Density currents of turbid water, originating from wave action during major storms or from muddy rivers, probably have played an important role in transporting clay and silt particles in the depths of the basin.

there, as in other reservoirs where underflows have been observed repeatedly, the mean velocity seems to be somewhat less than 1 m. p. h.

Turbid density currents, despite their slowness, have passed through Elephant Butte Reservoir on several occasions when that lake was more than 35 miles long and through Lake Mead even after that great reservoir had attained a length of more than 100 miles. If muddy underflows can persist for such distances there seems to be no good reason for supposing that, given the proper conditions, they cannot continue almost indefinitely.

In addition to the reservoir records, evidence that they do continue for long distances probably is to be had in heavy deposits of fine sediments, far from shore, on the bottoms of large lakes, or even on the ocean floor (fig. 22).

After a muddy underflow has reached a dam (fig. 23) there are three things that may happen to it. If the lake is shallow and discharging over a spillway crest, a part of the muddy water may, and probably will, be carried out with the clear water that is being taken from the reservoir surface. It is possible that the remaining muddy water will form a submerged lake from which much of the water can be withdrawn if the necessary outlets are available. If the lake is deep, and the outlet works are placed at relatively high levels, then the underflow must come to rest as a submerged lake in

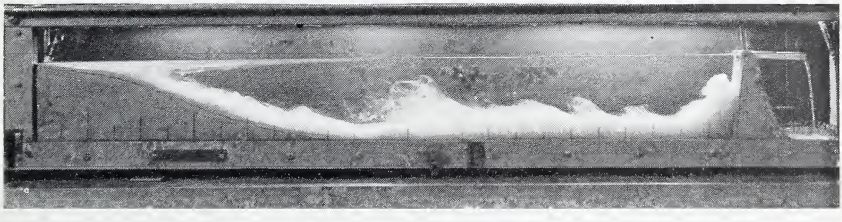

FIGURE 23.—When a flow reaches the dam it rises against the face and then recoils upon itself as a surge wave.

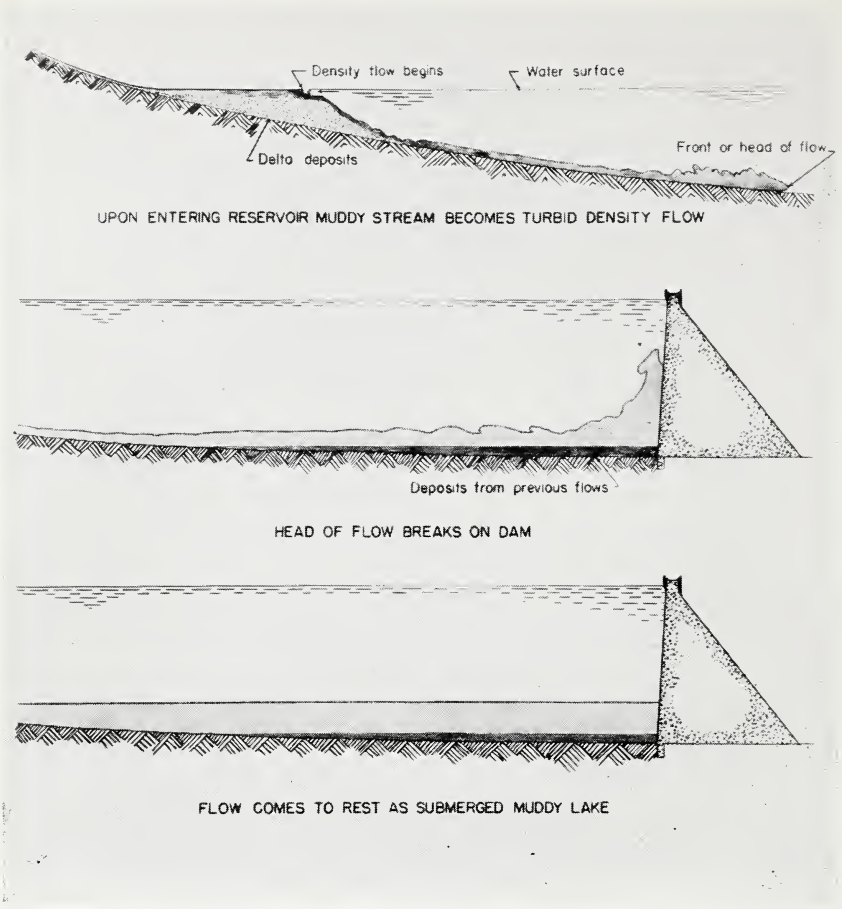
Density flow begins
Water surface
Front or head of flow
Delta deposits
UPON ENTERING RESERVOIR MUDDY STREAM BECOMES TURBID DENSITY FLOW
Deposits from previous flows
HEAD OF FLOW BREAKS ON DAM
FLOW COMES TO REST AS SUBMERGED MUDDY LAKE

FIGURE 24.—The history of a turbid density flow.

which the suspended sediment will settle rather slowly over a period of many months (fig. 24).

SUBMERGED LAKES CHANGE UNDERFLOWS TO INTERFLOWS

During the settling process a submerged muddy lake decreases in depth and, at least for a time, in surface area. Since this shrinkage occurs without loss of sediment, the density of the muddy mixture must increase. It requires only a few hours for the turbid water to become so dense that subsequent underflows may be forced to move along the interface as interflows. The new flow may disturb deposits below the interface and its density may thus be increased by mixing with the impounded muddy water.

Figure 25, *A* presents data that were obtained by the United States Bureau of Reclamation at a sampling station located midway between the upstream intake towers at Boulder Dam (fig. 25, *B*). An examination of these data reveals that at least five flows of turbid water, three of which were conspicuous, reached Boulder Dam between Agust 31, 1939 and June 2, 1941.

Columns 9, 10, 18, and 19 give the data on the two flows that are not so plainly recorded. Each of these flows was preceded by a period of several months during which the settling process seems to have progressed with little or no interruption, as indicated by the numbers expressing sediment concentration in pounds per cubic foot at elevations indicated by the dashed lines.

Periods of underflow apparently cause a pronounced decrease in sediment concentration near the surface of the muddy lake. An examination of the data in column 2 shows that, not only does the concentration increase with

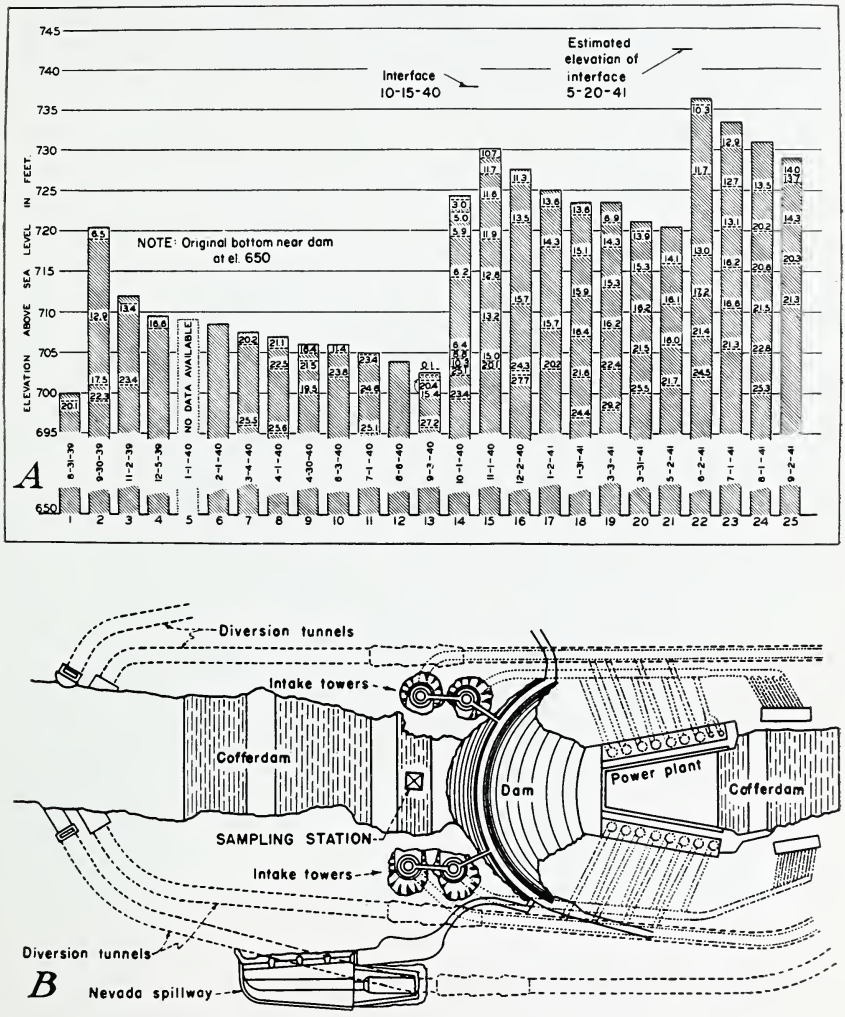

FIGURE 25.—*A*, Diagram showing monthly variations in depth of muddy water in submerged lake at Boulder Dam, August 31, 1939, to September 1, 1941. Numerals in columns represent sediment concentrations, in pounds per cubic foot at elevations indicated by dashed lines. B, Diagram showing location of sampling station at which data were obtained.

depth, but that there is a definite speeding up of the rate of increase with depth between elevations 699 and 701. This is particularly interesting because the surface of the submerged lake was at elevation 700 before the underflow of September 1939 arrived. The concentration data, therefore, seem to indicate that the underflow arrived at the dam as an interflow on the surface of the muddy lake, with a minimum of disturbance to the sediments previously impounded.

An even more striking example is shown by data included in columns 13 to 16. Measurements taken on September 3, 1940, indicate that the interface was at elevation 702.5, and that a density current was just beginning to overtop the cofferdam immediately upstream from the sampling station. Three months later a definite increase in sediment concentration still was detectable near that elevation.

Field evidence is too meager to permit conclusions regarding the sediment concentration in active underflows. In all probability it increases from top to bottom in any particular density current and rarely exceeds 5 or 6 pounds per cubic foot on bottoms that slope only a few feet per mile.

Although the sample recorded at the top of column 14 shows a sediment concentration of only 3 pounds per cubic foot, evidence indicates that the interface was settling. It was 1.7 feet lower 3 days later, and it would not be wise to assume that a density current was in progress on October 1, when the sample was taken. The interface began to rise sometime between October 4 and 7, and continued rising until it reached elevation 737.6 on October 15. Samples taken throughout this period of increasing depth indicate a sediment concentration of from 5 to 6 pounds per cubic foot within 2 feet of the interface.

Since the sediment concentration within 10 feet of the interface ranged from 3 to 6 pounds per cubic foot on October 1, it is probable that the big flow that began to arrive a few days later caused great disturbances in the upper portion of the submerged lake. When concentrations at the surface of the muddy lake are in excess of 14 pounds per cubic foot, fresh flows apparently follow along the interface and disturb the water below it little, if at all. There is no evidence that the October flow arrived upon a lake surface that was dense enough to support it without difficulty. It seems entirely possible that it was thoroughly mixed with the upper few feet of the impounded muddy water. If so, the inflowing current must have increased in density during the mixing process, and there is little likelihood that it arrived at the dam "riding" on the interface.

It should be noted, perhaps, that the surface of the submerged lake is just as real and definite as the plane of contact between air and water at the surface of a lake (fig. 26). At times a dense fog overlies the ocean, but this does not make the interface of the water and the atmosphere any less definite. Column 13 furnishes a good example of "foggy" water at the surface

U. S. Bureau of Reclamation

FIGURE 26.—Within the transparent walls of the sampler a portion of the muddy interface has been brought up from a depth of 475 feet beneath the surface of Lake Mead. The line between clear and muddy water is fairly distinct despite disturbances produced by the sampling operation. The sediment concentration immediately below the interface was about 10 pounds per cubic foot when this sample was obtained on June 6, 1941.

of the submerged lake. The sediment concentration immediately below the interface is approximately 200 times as great as it is immediately above.

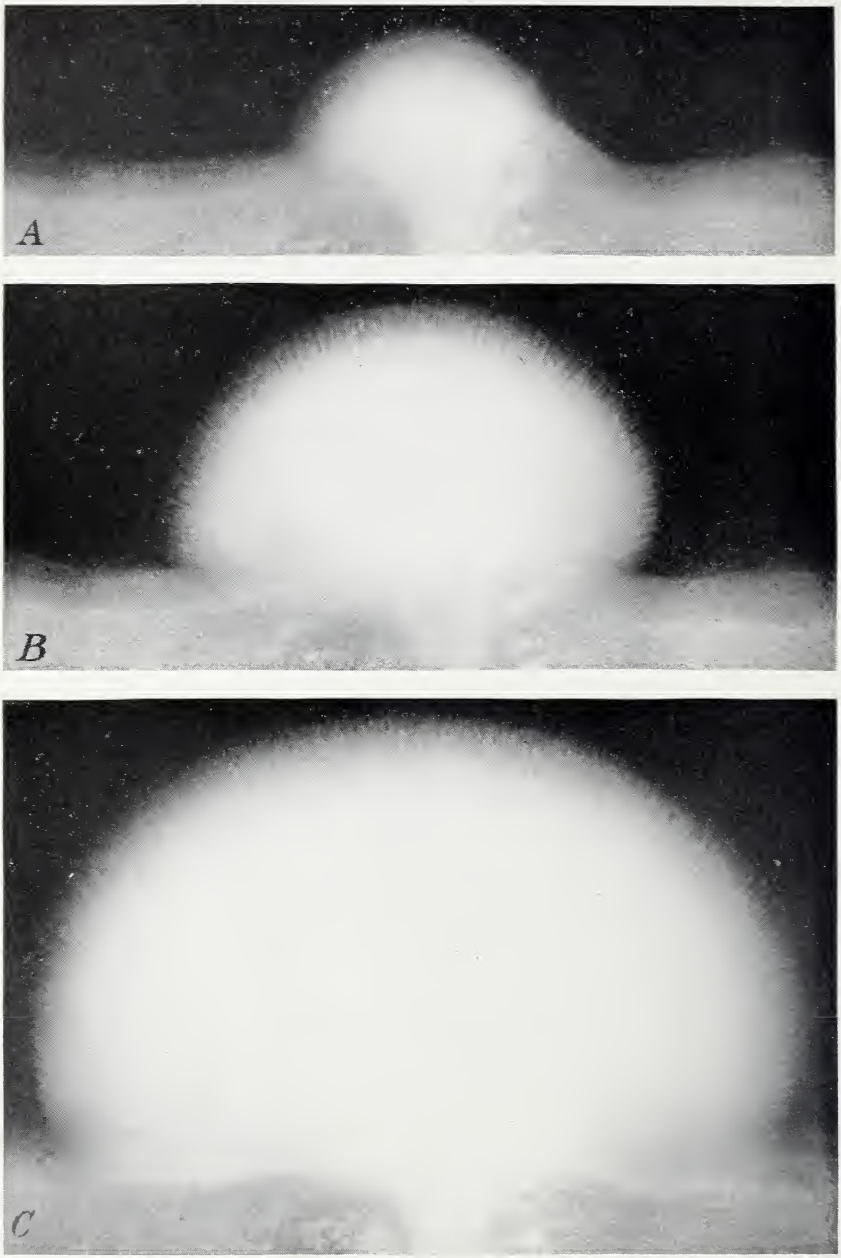

FIGURE 27.—Three "airplane" views showing the growth of an area of overflow in a laboratory reservoir.

When a turbid density current is passing through a reservoir, waves may be formed on the interface, much like the waves on the surface of a body of

water, and these even may have their crests swept off by overlying water in much the same manner as the tops are swept from surface waves by wind. This produces a layer of slightly turbid water above the underflow, and this new layer may have its density increased further by additions of muddy water from the breaking crests until it, too, is heavy enough to move as a density current. In any event it is dragged along by the original underflow and easily may be mistaken for the main current by an observer stationed on the surface. This new layer may give very erroneous impressions as to what is actually taking place at and below the original interface, because it hides the nature of the activity beneath as completely as fog conceals the character of the earth's surface from an aviator.

Although attention has been centered upon the behavior of turbid density flows, the only statements that do not apply equally well to underflows produced by differences in temperature or by dissolved matter are those dealing with the settling of suspended sediments and with the phenomenon of turbidity.

The Behavior of Overflows

Overflows are surface density currents that occur when the inflowing stream is less dense than the reservoir. Unlike underflows, they have no sloping channel to occupy, but must spread out upon a horizontal surface (fig. 27). Ideally they take the form of semicircles that expand with decreasing velocity, but their typical outline may be altered greatly by the wind or by other surface currents (fig. 28). As a general rule they move progressively more slowly.

M. L. Natland

Figure 28.—A surface layer of muddy water being carried down the coast by wind and shore currents.

A few gallons of water poured in the gutter of a gently sloping street may race along as a miniature flood and continue to flow for hundreds of feet, but the same quantity of water poured upon a level floor spreads in a circle that expands always more slowly and soon comes to rest. The two flows are unlike in behavior for the very reasons that account for the differences in the characteristic manner of flow of underflows and overflows.

A turbid density current drags along an overlying clear or slightly turbid layer of water, in much the same manner that wind, in passing over a body of water, tends to drag the surface layer. Any surface current, whether due to wind or other causes, may greatly alter the typical semicircular form of the overflowing layer (fig. 28).

Although the waves created on the surface by a gentle breeze may seem insignificant in size they may create relatively huge waves at the interface. At times the crests of these waves break violently and provide an effective mechanism for mixing the overflowing and the supporting strata. Many overflows, consequently, are short lived.

Muddy fresh streams that overflow the ocean often are mixed with the salt water in this manner, but the entire overflow does not plunge suddenly beneath the surface as does a turbid river after entering a reservoir. This is because the mixing is localized and, consequently, one mass of muddy water may be made heavy enough by the admixture of salty water to sink through the interface before the adjoining masses have become sufficiently dense to do likewise (fig. 29). The heavy portion breaks away and settles as a distinct unit, much like a balloon settling in air.

The same type of settling occurs in laboratory reservoirs when warm muddy water overflows a cold lake (fig. 30). No waves are needed here to cause the necessary increase in density since this is accomplished by the rapid change in temperature that takes place at the interface where the

M. L. Natland

FIGURE 29.—As muddy surface water mixes with the underlying salt water it becomes heavy enough to break through the interface and settle, allowing streaks and patches of clear water to reach the surface.

cold and warm layers are in contact. In the laboratory there is a union of the individual masses when they reach the bottom, and a typical turbid underflow makes its way along the sloping reservoir floor. It is reasonable to believe that a similar change from overflow to underflow may take place in nature, because the same type of settling through the interface has been observed (fig. 31). However, as yet there is no field evidence upon which to base such a conclusion.

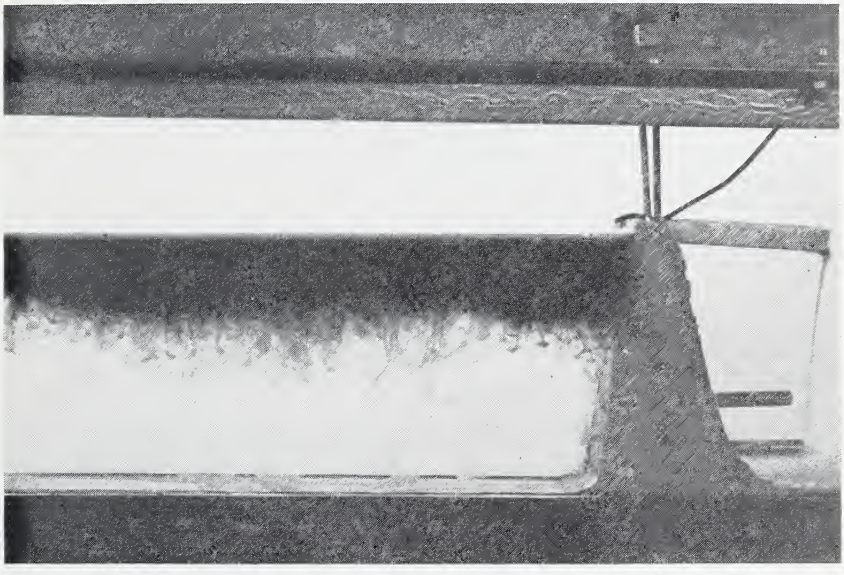

FIGURE 30.—Small masses of warm muddy water breaking through the interface as they are made heavy by contact with the cold water beneath.

The propeller of a motor boat passing through a turbid overflow mixes the lighter surface water with the heavier clear water beneath. Often this mixture settles quickly behind the boat and leaves a trail of clear water that may remain for several minutes until the slowly moving surface layer can flow over it again (fig. 32).

If the turbid layer is submerged a few feet the trail left by the boat becomes muddy, because the propeller creates very great disturbances at the interface and thus clouds of muddy water are brought to the surface. The propeller need not reach the interface for this to happen. Following an underflow of turbid water at Lake Lee, near Monroe, N. C., it was observed that "small boils" of muddy water were brought to the surface wherever motorboats went, even in the lower part of the lake where there may have been more than 10 feet of clear water above the interface.

The Behavior of Interflows

Interflows have an upper and lower interface, at each of which mixing may take place through the action of waves produced by the current. The meager field data now available indicate that submerged turbid lakes

M. L. Natland

FIGURE 31.—Muddy river water mixing with sea water and then settling through the interface, possibly to produce turbid underflows on the ocean bottom.

M. L. Natland

FIGURE 32.—A motorboat leaving a trail of comparatively clear water as it passes through an overflow of muddy river water on the ocean surface.

do not have a horizontal surface, but rather one that slopes toward the dam approximately 1 foot per mile. This makes it possible for some interflows to maintain a reasonable velocity and to travel long distances in a comparatively short time. The turbid water that reached Boulder Dam in May 1941 must have traveled not less than 30 miles as an interflow upon exactly such an interface.

Not all interflows, of course, move upon a favorable bottom slope. Many, as the result of the pressure gained through an increase in their own depth, are able to force their way along a horizontal interface of the kind that may be found between strata that differ only in temperature or salinity. The density of the interflowing layer may differ from that of the others by as little as 0.01 percent (1 part in 10,000) and, if so, it is only with great difficulty that it wedges its way along an interface. It is almost sinking in the heavier layer beneath, nearly floating in the lighter one above (fig. 33). Gravity alone moves it, but this force has been almost completely balanced by buoyancy. The little that remains is made even less effective because the lower interface is actually or nearly horizontal. Such currents, therefore, frequently move no more than a few hundred feet per day.

FIGURE 33.—A sediment-laden interflow, forcing its way between layers of clear and muddy water. Interflows result also from differences in temperature or salinity.

Whether a fluid of intermediate density is flowing into or out of a reservoir, the less it differs in density from adjacent layers, the greater is the difficulty in moving between them. This is a simple, but a very important fact that must be constantly kept in mind when stratified flows are used in operating a reservoir.

SOME FACTORS GOVERNING THE WITHDRAWAL OF LAYERS

A submerged outlet draws water toward it from all directions. If all the water within the reservoir is in every respect the same, the outlet will draw water simultaneously from all levels (fig. 34, *A*). When stratification exists, it becomes possible to withdraw water from a single layer. However, unless the diameter of the outlet is small in relation to the thickness of the layer, or the rate of withdrawal very slow, or the difference in density between the one layer and those above and below it great, there is little likelihood that withdrawal can be confined to a single stratum, as in figure 34, *D*.

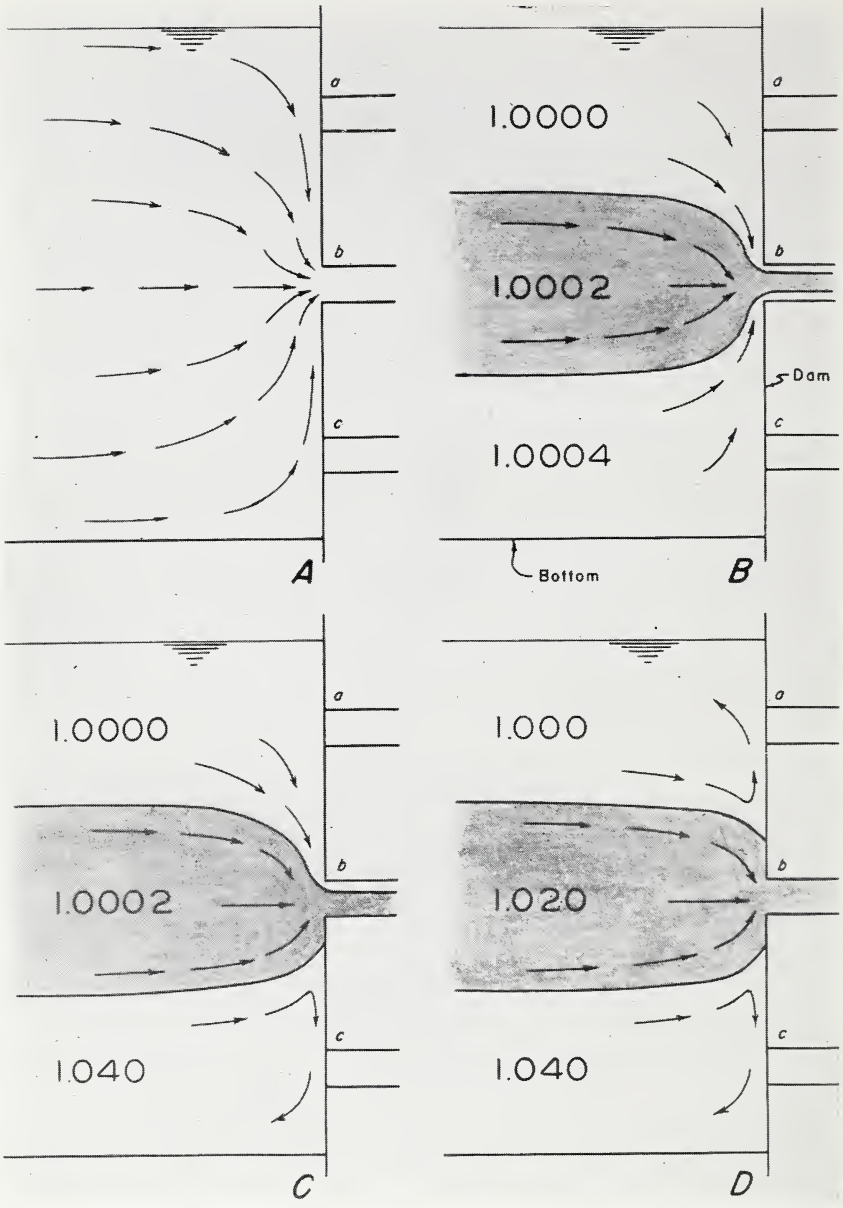

FIGURE 34.—Diagrams showing source of water withdrawn from unstratified and stratified reservoirs at constant rate. Numbers indicate relative densities of strata. *A*, From unstratified reservoir water is withdrawn simultaneously from all levels through a single outlet, *a*, *b*, or *c*. *B*, When differences in density are small, withdrawal continues from all levels through outlet *b*. If the rate of discharge barely is sufficient to insure withdrawal from all strata through outlet *b*, the same rate through *a* or *c* will not include water from all levels. *C*, When one stratum is much denser than others that differ only slightly in density, discharge through outlets *a* or *b* will come from top strata but not from bottom one. Through outlet *c* withdrawal will be from bottom layer only. By increasing the rate of discharge, water can be withdrawn from the overlying strata through outlet *c*. *D*, If the strata differ markedly in density, withdrawal may be confined to any stratum by selecting the proper outlet.

If withdrawal is to be confined to one layer, that layer must flow toward the outlet rapidly enough to supply the demand. Overlying water needs only to move downward, underlying water only to move upward, while that of the selected layer must move forward and, perhaps, encounter difficulties as great as those met by either of the other layers. As a result the outlet may, and frequently does, draw its supply from several layers (fig. 34, *B*, *C*).

If any one layer is to supply the entire discharge, the adjacent layers must be buoyed up or held down by a force greater than the suction exerted upon any portion of them by the outlet, as shown by figure 34, *D*. In this instance the entire outflow is supplied by the middle stratum, at the center of which an outlet is open. The discharge could be confined to one of the remaining layers by opening outlet *a* or *c* and closing outlet *b*.

SOME POSSIBLE APPLICATIONS OF STRATIFIED FLOW

After this description of the behavior of stratified flows it may be of value to study the operations of an imaginary dam at which the outlet works and special equipment were designed with the knowledge that stratification could and should be used whenever an improvement would result in the various services such a project has to offer.

Blue Lake and Ideal Dam will serve this purpose admirably. The dam is located on the Murky River at the upper end of Rock Canyon. At spillway level Blue Lake contains approximately 6,000,000 acre-feet, extends 44 miles up the Murky and nearly 20 miles up Clear Creek, a principal tributary. Granite and Gypsum Creeks, neither of which flows more than half the time in a normal year, are the only other streams worth mentioning that discharge directly into the lake (fig. 35). From February to June, Granite Creek brings water from the melting snows of the White Mountains, and then may cease flowing until the late summer rains renew its supply. Gypsum Creek carries very little water other than that of the flash floods produced by the torrential rains of August and September. It drains a badlands area, and its waters are both muddy and brackish.

At the lower end of Rock Canyon, about 50 miles below the dam, lies the head of Pleasant Valley, where 280,000 fertile acres are under irrigation. A new aqueduct with a capacity of 30 second-feet runs from Blue Lake down the Murky River for 82 miles carrying domestic water to the 63,000 inhabitants of Richfield, the principal city in Pleasant Valley. For the citizens of Richfield and others who live in Pleasant Valley and beyond, Blue Lake affords a vacation spot where fishing, swimming, and boating can be enjoyed at a moderate cost.

Since the completion of Ideal Dam, ditching has been undertaken in Sandylands Valley, immediately below Pleasant Valley, where 35,000 acres can be brought under irrigation. The soil, as the name of the area suggests, is very sandy, and there are many places where the canals cross deposits that are composed largely of coarse sands and fine gravels. Even in these

sections the canals have not been lined, because of a belief that the muddy water of the Murky River can seal any canal, no matter how much of a sieve it may be.

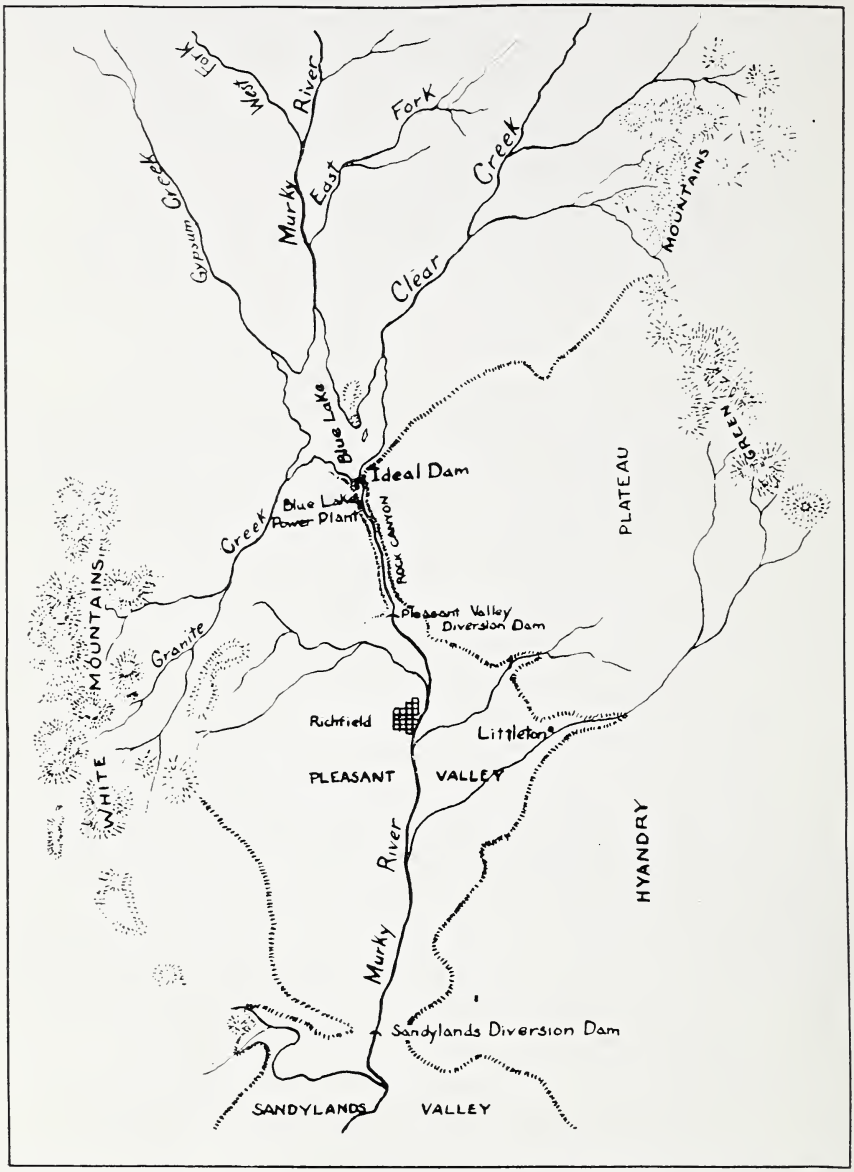

FIGURE 35.—Map of the "Blue Lake-Pleasant Valley region."

The Blue Lake Power Company has a hydroelectric plant at the dam that supplies power to the two valleys and to Industro, a thriving manufacturing city on the Murky, about 400 miles below the dam.

Before the construction of Ideal Dam, the flood damage was often serious at Richfield and Industro, but now Blue Lake is expected to eliminate this hazard for the cities and farm lands down the river. The top 15 feet of the normal storage area is reserved specifically for flood control, and, if in case of emergency this proves insufficient, drum gates can be used to raise the spillway crest an additional 12 feet.

On the morning of July 1 the superintendent of Blue Lake is in the control room at the dam planning the program of operations for the immediate future. He examines his mail. There is a request from Sandylands for confirmation that the muddy water, tentatively promised on June 18 for July 6 delivery, will arrive on schedule. Twenty miles of new canals are leaking badly and, therefore, the muddier the water is the better it will suit the operators. The Richfield Chamber of Commerce calls attention to the fact that July 4 comes on Saturday and requests a report on the probable water temperatures that may be expected at Blue Lake bathing resorts. On the first anniversary of the beginning of flow in the new aqueduct the head of the Richfield Water Department writes, and, jokingly, orders water for the next century, stipulating that it be of the same quality as that supplied during the past 12 months. Continuing in much the same style, the letter states, "The water you are supplying lacks only four things: Harmful bacteria, color, flavor, and a certain flinty hardness with which the citizens of Richfield had to contend during all the years water was taken directly from the river."

The superintendent recalls the struggle a few farsighted citizens had to obtain funds for an aqueduct that would bring the best Blue Lake water directly to the waterworks at Richfield with its purity and clearness unspoiled by a river journey. There were times when the efficient operation of the reservoir made it necessary to release water that was unfit for man or beast. There will be another such situation at 2 p. m. tomorrow, but there will be no complaints from Richfield. The curious always ask how such muddy water can come from so clear a lake. A few farmers who fail to read the notice that no water is to be taken from the river at the Richfield Diversion Works on July 4 and 5 may become a little excited because of upset plans for irrigating the east eighty, but that will not create too serious a situation.

The superintendent moves half a dozen switches and starts the reservoir condition-indicators. Six chart-covered drums move, stop for 30 seconds, and then move again, recording the surface temperature at the dam and at five sampling stations distributed at key points in the reservoir. Recorded also are the density, salinity, and turbidity of the water, as well as the velocity and direction of currents. Every 30 seconds additional figures are recorded on the charts, and the drums move again as similar data are gathered, at 10-foot intervals from the surface to the bottom of Blue Lake.

The new data stations, housed on anchored rafts and controlled from the dam, make it possible to obtain a detailed summary of conditions through-

out the entire reservoir in the space of 20 minutes. Formerly it took a 4-man sampling crew 2 days on the lake and a week in the laboratory to gather and plot as much data. Reports of this kind no longer arrive days too late to be of any use in operating the reservoir. No longer is there any question as to where the inflow is coming from, because every 10 minutes a report is received automatically from gaging stations on each of the principal tributaries. The superintendent has an instrument panel that tells him as much about his reservoir as the panel in an airplane tells the pilot about his ship.

The superintendent studying his data sheets finds that the 20-foot-surface layer shows a variation in temperature of only 1.1° F. at the dam, falling off from 75.4° F. (fig. 38), and that this stratum is remarkably uniform throughout the entire reservoir. That sets a new record for the first week in July, and is not exactly an accident. No water went over the spillway during the spring floods because withdrawal from submerged outlets was begun early and has continued. Water for power and irrigation is discharging through outlets that are 270 feet below the surface near the middle of a stratum about 120 feet thick. The temperature in that layer varies from 54.6° to 53.2° F., and the water has a hardness that the housewives in Richfield do not appreciate.

At the moment they are being supplied from a stratum of soft snow-water that arrived during March and April from the mountainous areas drained by Granite and Clear Creeks. It is still detectable by a slight temperature break midway in a 200-foot zone that extends downward from the warm surface layer, and in which, except for that one irregularity, the temperature drops steadily from 74° to 54° F. This particular band was much more distinct a month ago and probably will have vanished in another 30 days, but it is still possible to draw off the 25 second-feet needed for Richfield.

From 340 to 370 feet below the surface is a layer of uniform temperature, 53.2° F. from top to bottom. The superintendent knows that layer well.

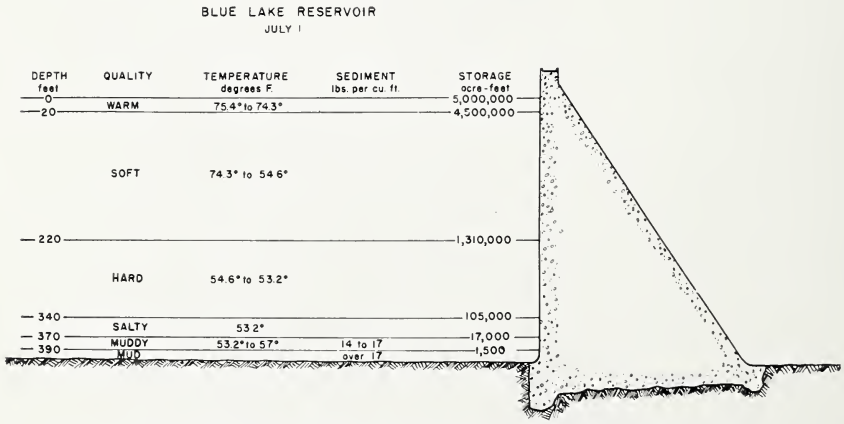

Figure 36.—Diagram showing stratification in Blue Lake Reservoir on July 1.

It is salty water from Gypsum Creek that has been accumulating for 3 years while Industro was obtaining adequate storage facilities and Richfield was building its aqueduct. Next winter, when there is no demand for irrigation water, he will warn Industro to fill its reservoirs and prepare for 3 days of salt water, 5 days of fresh, then 3 days of salt, and so on until all 90,000 acre-feet has passed on to the ocean.

Below the salty stratum lies a 20-foot layer of muddy water that has a density of 1.140 at the top and 1.168 at the bottom. It reached the dam as a turbid underflow from the Murky River about the middle of the afternoon of May 27 and has been steadily becoming more dense, until now it can be withdrawn with the greatest speed and a minimum loss of water. He telephones to warn the chief operator at the power plant he'll "be generating electricity with mud from 2 p. m. tomorrow for several days because down at Sandylands they will be trying to make some leaking canals hold water." At last, the chief operator has become convinced that the superintendent had told the truth when he assured him that there was not a single particle with a diameter as much as one-five-hundredth of an inch in an acre-foot of the sediment that had reached the dam in underflows, and, therefore, his turbine runners would not be harmed.

"All right, just leave the kilowatts in it," is the operator's reply.

What a change in attitudes toward muddy water! Four years ago, when the dam was nearing completion, it seemed that everyone was insisting that all the mud should be kept in the reservoir. Now there are requests for it, and in the next few days sediments that eventually would have occupied perhaps 3,500 acre-feet of reservoir space forever will move down to Sandylands where they are wanted, or they will flow on to the ocean.

Down in Pleasant Valley they are having trouble with moss and weeds in ditches where there was little or none before the completion of Ideal Dam. There is a growing belief that this growth has taken place because sunlight now can penetrate the clear water, reach the green leaves of the plants, and thus enable them to make starch and live. Perhaps this would not have happened if the water in the ditches had been muddy. Only recently it was suggested that possibly a week or two of muddy water would kill the weeds and eliminate a large item from the maintenance costs of the canal system. The idea is spreading and in a few more months the superintendent may get a request for turbid water for this purpose. If he does, the first underflow that reaches the dam after the salty water has been discharged will be rushed through before it has time to settle any more than is made necessary by the need for controlled outflow. It must not be so heavy with silt that it will cause costly deposits in the canals or seal the soils of Pleasant Valley.

The gaging-station records show that West Fork is rising rapidly. It has been dry for almost two weeks, and normally is not flowing in July. A flash flood (fig. 37) on West Fork usually means a turbid underflow in Blue Lake, and it is probable also that Gypsum Creek will go on the rampage,

FIGURE 37.—A flash flood on the Little Colorado River, February 8, 1937: *A*, This photograph was made at 12:00 m.; *B*, the same view at 4:40 p. m. Notice that almost the entire area shown in *A* has been completely inundated in a period of less than 5 hours, during which an insignificant stream has become a river nearly 2 miles wide.

because both streams have their headwaters in the same badlands area. If an underflow does take place the new sampling stations will give enough data so that its volume can be determined rather accurately long before the muddy water reaches the dam.

Perhaps there will be a demand for more mud to seal the canals down in Sandyland, or possibly the farmers down there will be ready to attempt to improve their too sandy soil by using the clay that is in muddy water. If so, they should have it before settling makes it too concentrated. That calls for quick action in order to make the necessary contacts with the farmers' organizations in both valleys. It may be a good opportunity also to see what muddy water can do to weedy ditches.

In any event the muddy water will be withdrawn from Blue Lake because reservoir capacity, once lost, is almost certainly lost forever.

The superintendent knows that it takes planning to operate a reservoir properly but when his instruments give him warning—tell him what is happening, and what is almost certain to happen, even answer his questions before he can ask them—that makes it easier. But plans are of no use without the equipment to carry them out. Blue Lake has that, too, in the outlet works at the dam, designed so that water can be withdrawn from any level at any time, or from several levels at once. Expensive? Certainly. But the dividends they pay in a dozen ways are many times more than the cost.

THE QUANTITY OF SEDIMENT CARRIED BY UNDERFLOWS

Blue Lake and Ideal Dam do not exist, but the time has come when reservoir operating technique can and, in many instances, should make use of density flows. The importance of such currents as agents for the transportation of fine sediments is well illustrated by certain data gathered in recent years by the U. S. Bureau of Reclamation at Lake Mead, and presented, in part, as figure 25, *A*, of this publication.

The tunnel through which turbid water previously had been discharged was closed permanently on May 1, 1936. Prior to August 31, 1939, a submerged muddy lake, with its surface at elevation 700 feet, had formed at Boulder Dam (fig. 25, *A*). One mile upstream the surface was at elevation 712, and 20 miles upstream, in Boulder Canyon, it was at elevation 737. The rise of 12 feet in the first mile above the dam was caused by a cofferdam, the crest of which is at elevation 720 (fig. 38).

During the first 4 years of storage many of the turbid density flows that reached the cofferdam failed to overtop it. For instance, between October 1, 1938, and September 30, 1939, at least six muddy flows arrived, but only two of them, the first and last of the series, filled the basin between the cofferdam and Boulder Dam. Of the remaining four only one appears to have risen to the crest elevation.

To estimate the volume of the submerged lake, it was assumed that the interface extended upstream from the cofferdam and through the point in

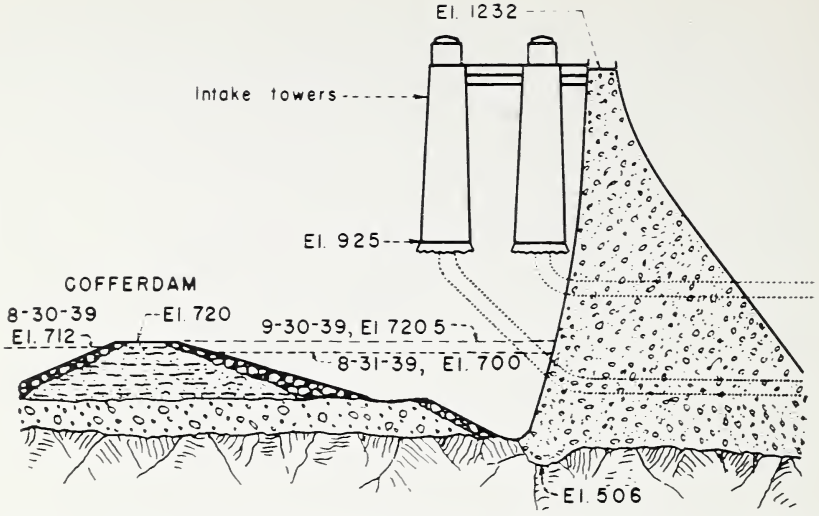

FIGURE 38.—Diagram showing the location of the cofferdam in lower Lake Mead. The dashed lines indicate the surface of the submerged muddy lake in August and September 1939.

Boulder Canyon without appreciable change in slope. If so, it intersected consolidated bottom deposits of rather coarse material about 35 miles from Boulder Dam at elevation 755. It was assumed further that turbid water and unconsolidated muddy deposits occupied the entire reservoir basin below elevation 711, and 50 percent of the basin between elevations 711 and 755. This, according to capacity tables for Lake Mead, would be approximately 247,000 acre-feet. Estimating the mean sediment concentration on August 31, 1939 at about 25 pounds per cubic foot, the muddy lake contained 134,700,000 tons of solid matter, or 103,000 acre-feet at 60 pounds per cubic foot. This sediment, all transported by density currents, had accumulated at the rate of almost 780,000 tons per week during the 40 months between May 1, 1936, and September 1, 1939.

During the latter half of September 1939 the muddy interface rose approximately to elevation 725 between the intake towers at Boulder Dam. By referring to figure 38 it can be seen that by the end of the month it had settled to elevation 720.5. Other data show that it was then at elevation 745 in Boulder Canyon and, consequently, may be assumed to have intersected the coarser bottom deposits somewhere between 35 and 40 miles above the dam [5] at approximately elevation 765. The volume of the submerged lake, according to the system of estimating used previously, was roughly 315,000 acre-feet, or 67,700 acre-feet greater than it had been 1 month earlier. In this newly arrived muddy water the mean sediment concentration appears to have been approximately 10.3 pounds per cubic

[5] The presence of these bottom deposits has been determined by soundings made by the U. S. Bureau of Reclamation.

foot on September 30. In this one period, then, nearly 15,200,000 tons of very fine sand, silt, and clay had been brought to the lower end of the reservoir where, if it eventually compacts to 60 pounds of solids to the cubic foot, it will occupy about 11,600 acre-feet of valuable storage space.

By using the same method of calculation it can be estimated that between September 3 and October 15, 1940, underflows brought more than 250,000 acre-feet of muddy water into the submerged lake, and thus transported approximately 47,700,000 tons of sediment or 36,500 acre-feet at 60 pounds per cubic foot. Between May 2 and June 2, 1941, underflows brought an additional 34,200,000 tons, or 26,200 acre-feet, at 60 pounds per cubic foot. In a period of less than nine months, September 3, 1940, to May 20, 1940, the quantity of stored sediment increased 54.6 percent, and reached the impressive total of nearly 232,000,000 tons, or enough to occupy 177,500 acre-feet when compacted to 80 pounds per cubic foot.

Density flows, then, were transporting fine sediments into lower Lake Mead at the rate of 875,000 tons per week during the 61 months immediately following the closing of the tunnel on May 1, 1936. At the end of that period the volume of muddy water was approximately 388,000 acre-feet, or 1.35 percent of the total original capacity of Lake Mead at the elevation of the fixed spillway crest. If it is assumed that these sediments eventually will compact to 60 pounds per cubic foot, the density currents are transporting material sufficient to occupy 1 percent of the original spillway-crest capacity each 8.2 years. Perhaps this loss is made necessary by the many needs Lake Mead must supply, but it seems reasonably certain that, with proper outlet facilities, from 75 to 90 percent of this sediment could have been carried beyond the dam by the use of stratified flow.

To see what this might mean in terms of the total life of Lake Mead, assume that, under the present conditions, the reservoir will become completely filled with sediments in 200 years. According to the estimates above, material transported by density currents will occupy approximately 24 percent of the original storage space at that time, provided that none is discharged, and the average concentration has become 60 pounds per cubic foot. If only 75 percent of this material could be wasted instead of stored, the life of the reservoir could, apparently, be increased by 35 or even 40 years. This is not an unimportant fraction of the total life of the project.

DENSITY CURRENTS CAN PROLONG LIFE OF RESERVOIRS

Those who are most familiar with sedimentation in American reservoirs are of the opinion that the lives of many of them may be substantially increased by making use of the transporting power of density currents. If, for example, it would be possible to lengthen the useful life of Lake Mead by 20 percent, it may be possible to do even better for reservoirs on rivers

that carry a sediment load in which the fine particles are proportionately more abundant than they are in the Colorado River.

If the maximum benefit is to be obtained from the use of stratified flows as transporting agents, they should be put to work as soon as possible after storage has begun in a new reservoir. There are two reasons for this. During the operation of Lake Arthur Reservoir, in South Africa, it has been found that after sediment-laden water has been impounded it will not move readily, as a stratified flow, if the concentration exceeds 25 percent by weight (18.6 pounds per cubic foot). Its discharge cannot be indefinitely postponed, therefore, without serious consequences. Possibly the deposited sediment could be resuspended by using hydraulic giants, or by other mechanical means, but such a program would involve very considerable costs.

A less obvious reason for the prompt removal of turbid water from a reservoir is that deposition of the suspended material decreases the bottom slope of the reservoir, and thus cuts down on the size as well as the quantity of material that can be transported. The slope of the interface at Lake Mead, after turbid water had been stored for 5 years, apparently was less than 1 foot per mile in the 35 miles immediately above the dam, whereas, the original bottom slope had been approximately 3 feet per mile.

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FIGURE 39.—A small tributary stream has cut through a deposit of fine sediment laid down in Lake Mead when the water level was higher. This sediment was composed almost entirely of the finer sands and silt, and was, in general, too coarse to be transported by a density flow.

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FIGURE 40.—A deposit of silt in Lake Mead in an area where there had been slack water at a sharp bend during a higher stage of the reservoir. The location is 98 miles from Boulder Dam.

Bottom slopes in large reservoirs rarely are more than a few feet per mile and, therefore, density currents cannot be expected to attain velocities that will permit them to carry any but the finest portion of the sediment load. Clays and the finer silts are transported readily, but it is to be expected that a portion of these fine sediments will be deposited along with the coarser silts and fine sands on the delta, or as bars (figs. 39 and 40). In the small reservoirs along the Pacific coast, bottom slopes sometimes exceed 100 feet per mile. On such slopes density currents can transport rather coarse sand, and are known to have plugged low-lying outlets that were in operation.

In certain reservoirs the problem is not one of the withdrawal of fine sediments, but rather one involving the removal of salty water from submerged pools near the dams. The withdrawal of a layer of this kind is comparatively difficult to accomplish without loss from more desirable layers, because the density differences are not as great as those that can be obtained by allowing muddy flows to concentrate by settling. This disadvantage is offset by the fact that, in most instances, the time of withdrawal can be almost indefinitely postponed, or the rate of discharge greatly reduced, without producing any very grave consequences. The loss of useful storage space, under such circumstances, may be regarded as temporary, as something that can be remedied without the aid of too heroic measures. Over a long period, however, it is economically unsound to store salty water in a reservoir from which fresh water must be wasted.

CONCLUSION

The study of stratified flow is still in its beginning. The need for accurate field data and careful field observations is great. With the construction of each new dam this need increases. Nearly all of our great western reservoirs are young, but the accumulation of strata, composed of water of undesirable quality, may go far toward impairing or destroying certain of their functions long before they become old.

Plans conceived and put into effect today can eliminate many of tomorrow's emergencies and postpone appreciably the time when our reservoirs become useless. The consistent and intelligent use of stratified flows can do much toward solving some of the present reservoir problems, as well as those of the future. A few reservoir operators recognize this fact in their practices, but they are, unfortunately, the exception rather than the rule. Perhaps, before any great advances can be made, there must come a wider realization of the fact that reservoir capacity is one natural resource for which no economically feasible substitute is, or perhaps ever will be known; a resource this generation has the opportunity, but not the right, to waste.